NASA
Reference
Publication
1101

June 1983

NASA-RP-1101 19830020139

Radiometer Requirements for Earth-Observation Systems Using Large Space Antennas

Lloyd S. Keafer, Jr.,
and Richard F. Harrington

25th Anniversary
1958-1983

NASA

NASA
Reference
Publication
1101

1983

Radiometer Requirements for Earth-Observation Systems Using Large Space Antennas

Lloyd S. Keafer, Jr.,
and Richard F. Harrington
Langley Research Center
Hampton, Virginia

NASA

National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

PREFACE

Developments in large, lightweight-structures technology, coupled with the unfolding reality of the capability of the Space Shuttle for carrying large payloads to orbit on a routine basis, have sparked interest in very large systems in space and in the missions to which such systems could be assigned.

The Large Space Systems Technology Program spearheaded initial efforts in this arena by the National Aeronautics and Space Administration, and missions employing large space antennas have received much attention. Earth-observation radiometry using large space antennas is one of the more demanding missions. Consequently, it is felt that the organization of Earth-observation-system requirements for performing radiometer missions, along with appropriate logic pointing to potential design trades, would provide a needed reference for scientists, technologists, system designers, and space planners.

CONTENTS

SYMBOLS

A	drag area
B	bandwidth, Hz
C	constant, K
C_D	drag coefficient
$C_D A/m$	spacecraft ballistic coefficient, m^2/kg
D	antenna diameter, m
EIRP	effective isotropic radiated power, W
F	resolution element (footprint), m^2
FOV	field of view, deg
f	frequency, Hz
g	gain
h	orbit altitude, km
IFOV	instantaneous field of view, deg
i	orbit inclination, deg
k	Boltzmann constant, $W\text{-}K^{-1}\text{-}Hz^{-1}$
m	mass
P	antenna power level
Q	orbit-repetition rate, repetitions per day
R_i	power-reflection coefficient of forward-directed input waves
S	edge-to-edge swath width, km
SST	sea-surface temperature, °C
T	temperature, K
T_{ant}	antenna temperature, K
T_B	microwave-radiometric brightness temperature, K
T_o	ambient temperature of reference load, K
T_{rec}	receiver-input noise temperature, K

T_{sys} system-noise temperature, K

ΔT radiometer sensitivity, K

t_d dwell time, sec

V orbit velocity, m/sec

W_s wind speed, m/sec

α attenuation factor of radiometer front end, neper

δ rms surface error, m

ε beam efficiency, percent

θ_c angular-resolution capability

θ_i incidence angle, deg

θ_r angular-resolution requirement

λ antenna operating wavelength, m

σ standard deviation

σ^2_{TA} variance of antenna temperature, K^2

τ postdetection integration time, sec

Abbreviations:

CONUS continental United States

dBm power level, referenced to 1 mW, dB

ESMR electrically scanned microwave radiometer

GEO geosynchronous Earth orbit

Geos satellite name

IR infrared

Landsat satellite name

LEO low Earth orbit

LSA large space antenna

Meteosat satellite name

MSU microwave sounding unit

Nimbus 6 satellite name

NOAA 5	satellite name
RFI	radio-frequency interference
rms	root mean square
SASS	Seasat A satellite scatterometer
SCAMS	scanning microwave spectrometer
Seasat	satellite name
SMMR	scanning multichannel microwave radiometer
Tiros N	satellite name
WARC	World Administrative Radio Conference

I. INTRODUCTION

The spacecraft research program at the National Aeronautics and Space Administration (NASA) is aimed at developing the technical foundation for future high-performance, cost-effective spacecraft systems. Development of large-space-antenna (LSA) systems is an integral part of the program. Consequently, it is appropriate to define measurements and missions that may need or utilize LSA systems and to delineate the corresponding performance and system requirements in order to guide the spacecraft and LSA-systems research. Three generic applications are considered to be "technology drivers": (1) narrow-band communications, (2) radio astronomy from space, and (3) Earth-observation radiometry.

Although the requirements for the three applications may be similar in many ways and a basic LSA system may respond to all of them, there may be other ways (e.g., orbit parameters and beam efficiencies) in which the requirements may be markedly different. The impact of such differences on the research and technology efforts must be assessed. This report addresses only the requirements for Earth-observation radiometry.

Current practical guidelines for LSA-systems development constrain the antenna-aperture range from 50 to 200 m and postulate that the first flight missions will occur in the early 1990's. The "new" information in this report is simply the selection of requirements for this antenna-size range projected to circa 1990. A preliminary report was published as reference 1. An attempt has been made in the present report to summarize the rationale for selection of these requirements in a progressive fashion, starting with Earth-observation needs and measurement needs addressable by an LSA radiometer and concluding with radiometer, orbit, and performance requirements for LSA systems.

II. EARTH-OBSERVATION NEEDS

General Needs

The following statements, taken from reference 2, offer a succinct summary of the objectives and future emphases of NASA's Earth-observation program:

"The Resource Observation program objectives include forecasting of agricultural production, exploration for mineral and energy resources, management of land use and water resources, and assessment of geodynamic hazards. Current efforts are concentrated in utilizing medium- to low-resolution instruments in a few spectral regions. Future emphasis will be on high-resolution (temporal, spatial, and spectral) studies in truly multispectral fashion, including magnetic, microwave, IR, visible, and stereo data."

"The Global Environment program objectives include monitoring and forecasting of global weather and local severe storms, assessment and forecasting of climate, monitoring and forecasting of ocean conditions, and assessment of air and water quality. The future emphasis will be on multi-instrument systems to measure a variety of phenomena simultaneously, and on geosynchronous observations."

The important feature of these statements regarding LSA requirements is that high-resolution sensing in the microwave portion of the spectrum is needed "to measure a variety of phenomena simultaneously," and that these measurements would be particularly useful in agriculture, hydrology, and weather- and climate-forecasting applications. Measurement of the natural electromagnetic radiation in the microwave portion of the electromagnetic spectrum can be employed in the remote sensing of atmospheric, ocean-surface, and land-surface parameters. Atmospheric parameters that can be sensed include water vapor, nonprecipitating liquid water (clouds), precipitating liquid water (rain), temperature profiles, and pollutants. Ocean-surface parameters that can be sensed include surface temperature, salinity, wind speed at the surface, water pollutants (such as oil slicks), sea-ice concentration, location of ice edge, and ice age. Land-surface parameters include soil moisture and snow cover.

For the observables listed, high resolution generally means spatial-resolution elements or footprints whose largest dimensions range from approximately 20 to 1 km, and also temporal-resolution elements or revisit intervals which range from approximately 4 days to 1 hr. Thus, the elements necessary to determine microwave frequencies, antenna-aperture size, and orbit-parameter requirements for LSA systems have been defined in a preliminary fashion by the needs of the NASA Earth-observation program. (See ref. 2.)

Key Measurements

Microwave-radiometry applications in the band from 30 to 6 cm (1 to 5 GHz) have long been identified as a "driver" in the development of large space antennas. Soil-moisture content, sea-surface temperature, and salinity are the key geophysical parameters of interest for remote sensing in this wavelength region. Physical models and experimental demonstrations have validated the theories relating microwave brightness temperature to these geophysical quantities. The development of future systems involves trade-offs between required spatial resolution, swath width, revisit time, and data rate. The data in table 1, which lists requirements given in reference 3, were generated by scientists studying configurations of a multifrequency microwave radiometer.

TABLE 1.- KEY MEASUREMENT REQUIREMENTS

Measurand	Spatial resolution, km	Swath, km	Temporal resolution, hr
Sea-surface temperature:			
Open ocean	20 to 50	500 to 1000	48 to 72
Coastal zone	1	100 to 150	48 to 72
Salinity:			
Open ocean	5 to 10	500	72
Coastal zone	0.5 to 1	100 to 150	72
Soil moisture:			
Agriculture	25		48 to 72
Hydrology	3		48 to 72

The measurement of sea-surface temperature (SST) on a global basis is important to climate modeling, weather forecasting, the maritime industry, and the fishing industry. Resolution requirements in the open ocean vary from 20 to 50 km with swath widths as wide as 1000 km and temporal repeats as rapid as every 48 hr. In certain areas of the open ocean where large thermal gradients exist, such as the Gulf Stream in the Atlantic Ocean, higher spatial resolution on the order of 5 to 10 km might be required. (See ref. 3.) Sea-surface temperatures have been mapped with the Seasat SMMR microwave radiometer over an area in the western North Pacific Ocean. The range of the measurement was from 10°C to 29°C with a spatial resolution of 150 km. (See ref. 4.) A comparison with sea-surface-temperature measurements made aboard ships shows a difference whose mean is 0.22°C with a standard deviation of 0.75°C.

Measurements of SST from satellites (Geos, NOAA 5, Tiros N, and Meteosat) over cloud-free ocean areas have been made with high-resolution infrared radiometers. The Tiros N measurements have an accuracy of ±1°C with a spatial resolution of 1 km. Meteosat spatial resolutions are about 8 km. (See ref. 5.) Monitoring of SST on a global basis by using an IR and/or visible radiometer is limited to cloud-free regions. The application of high-resolution microwave radiometry could provide measurements in cloud-covered regions with an equivalent accuracy and a spatial resolution of 5 to 10 km. Recent work suggests that a high-resolution microwave radiometer can provide the necessary measurements of the atmospheric losses and thereby correction factors so that significant improvements in the accuracy of IR and/or visible radiometers can be achieved. (See ref. 6.)

Sea-surface-salinity measurements with spatial resolution better (lower) than 1 km for coastal-zone applications can be obtained by remote-sensing aircraft; consequently, salinity observations from space concentrate on the open ocean where moderate resolution measurements are required on a global scale.

A Soil Moisture Working Group was established during the Soil Moisture Workshop held at the Department of Agriculture in January 1978 to coordinate and develop an integrated plan of research. This group included members from NASA, universities, and other government agencies. This working group published their recommendations in the form of a plan given in reference 7. This plan discusses soil-moisture measurement requirements as they apply to agriculture, hydrology, and climate, and it presents a set of preliminary system requirements for each type of sensor system applied to each application. Table 2 summarizes these requirements as they apply to a passive microwave sensor.

TABLE 2.- SOIL-MOISTURE RESOLUTION REQUIREMENTS

Application	Radiometric resolution, K	Spatial resolution, km	Temporal resolution, hr
Agriculture	±1	<10	24 to 72
Hydrology	±.5	10 to 25	24 to 72
Climate	Not specified	100 to 200	71 to 144

Recent studies (ref. 8) to evaluate and quantify the relative merits of soil-moisture observations at a 1-km resolution rather than at a 10-km resolution reached these conclusions:

(1) Rainfall amounts from most storms in the central United States (U.S.) can be resolved on a 10-km scale with a 20-percent underestimate of the peak.

(2) For land features in the midwestern U.S., a 10-km radiometer resolution provides useful and representative soil-moisture measurements.

(3) Most crop-yield forecasts can be accomplished and improved with approximately 10-km resolution. A 1-km resolution in the central U.S. would benefit those concerned with details of soil moisture over regions where ponds and lakes cause radiometer ambiguities.

Reference 8 states that the soil-moisture content is proportional to the rainfall amounts over an area. In an analysis of over 400 central U.S. storm systems, a 10-km resolution was shown to be the characteristic scale size for the amount of rainfall. Further, an analysis of Landsat images showed that land features were accurately represented by a 10-km scale size. In the central U.S. and in similar agricultural areas, soil-moisture requirement needs may be met with 10-km spatial resolution. Finer (smaller) resolution, on the order of 1 km, however, may be required in areas where (a) radiometrically interfering water bodies are more prevalent, (b) terrain variability occurs on a smaller scale, (c) fields and kinds of crops are more variable and diverse, and (d) irrigation patterns exhibit fine spatial structure. In summary, for soil-moisture determinations, a spatial resolution of 10 km could be useful; however, a resolution of 1 km is desirable for the majority of agricultural, hydrological, and climate applications.

The desired intervals between revisits range from 1 to 6 days (table 2) with most of the applications being satisfied within 3 days. Irrigation scheduling, reservoir control, crop forecasting, and flood assessment demand frequent revisits. It is critical that the swath width be sufficiently large to meet this need and maintain contiguous coverage over large geographic areas vital to full utilization of the various measurements, for example, soil-moisture measurements over major farm belts in the latitude band from 30° N to 50° N.

Summary of Measurement Needs

Measurement needs for all applicable geophysical measurands for an LSA radiometer mission are shown in table 3. The measurands are listed at the top of the table. Soil moisture, sea-surface temperature, and salinity are the key measurements requiring the use of an LSA radiometer. The selected critical measurement requirements are discussed.

Range is listed in terms of the geophysical quantity and varies with each measurand. Soil-moisture range requirements are set by agricultural needs. However, water-pollutant requirements are paced by the sensing of oil-spill thickness; and ice measurements, by being able to determine boundaries. In section IV, these ranges are converted to, and listed in, terms of "brightness temperature," the quantity actually measured by the LSA radiometer.

Accuracy also is listed in terms of the geophysical parameter. Again, soil-moisture requirements for agricultural applications are the critical ones. In section IV, accuracy (including precision and sensitivity) requirements are translated into allowable error and noise tolerances in terms of brightness temperature.

TABLE 3.- MEASUREMENT REQUIREMENTS FOR LSA RADIOMETER

Selected requirements	Soil moisture	Sea-surface temperature	Salinity	Water roughness (winds)	Ice	Water pollutants (oil)	Atmospheric water vapor	Precipitating liquid water (rain)	Nonprecipitating liquid water (clouds)
Range	5 to 40% at depth of 5 to 10 cm	0 to 30°C	0 to 40 ppt	0 to 60 m/sec	Boundaries	Oil thickness of 0 to 1 cm	0 to 60 kg/m^2	0 to 100 mm/hr	0 to 10 kg/m^2
Accuracy	20% wet and 50% dry	1°C	1 ppt	2 m/sec	0.5 km linear	1-mm thickness	±2 kg/m^2 or ± 10%	±2 mm/hr or ±10%	±0.1 kg/m^2 or ± 10%
Spatial resolution ...	10 km (mandatory) to ≈1 km (desired)		10 km (mandatory) to ≈1 km (desired)	1 km	1 km	1 km	15 km	10 km (mandatory) to ≈2 km (desired)	15 km
Coverage	Farm belts	Oceans	Coastal zones	Oceans	Coastal zones and inland waters	Coastal zones	Global	Global	Global
Temporal-repeat intervals	Primarily 3 days, some 1 day		Primarily 3 days, some 1 day	3 days to 1 week	3 days to 1 day	1 day	1 day	1 day	1 day
Experiment lifetime	Several years	Several years	Several years	Several years	Several years	Several years	Several years	Several years	Several years

Climate applications have the greatest need for measurements over a long period of time. A precise specification is not needed for technology-development purposes, and, thus, the requirement for experiment lifetime is simply stated as "several years."

Large geographic regions must be surveyed. Contiguous coverage of these areas is vital to the full utilization of the various measurements, for example, contiguous soil-moisture measurements over major farm belts. In section III, this requirement is translated into swath width and orbit requirements.

The needs of most applications are met with temporal-repeat intervals (sampling or revisit intervals) of approximately every 3 days. A few applications, however, require repeats as often as once every day. Therefore, 3 days is considered the primary requirement for temporal resolution and 1 day is the secondary requirement. In section III, this requirement (along with coverage) is translated into orbit and swath-width requirements.

Many application needs are met with approximately 10-km spatial resolution. A number of applications, however, require resolutions as fine (small) as 1 km. Therefore, the selected spatial-resolution requirement ranges from 10 km (mandatory) to 1 km (desired). In section III, these spatial-resolution requirements are translated into orbit-altitude requirements; and in section IV, they are translated into main-beam efficiency and antenna aperture-size specifications.

An extremely wide range of measurement needs has been expressed by data users, especially for spatial resolution, temporal repeats, and geographic coverage. However, as will be shown later, LSA radiometers have severe limitations that force trade-offs regarding the requirements imposed by resolution and coverage needs on orbit parameters, swath width, antenna-aperture size, and accuracy. Even with an ideal system, LSA radiometers in the range from 50 to 200 m can promise only relatively moderate spatial resolution. Therefore, a prime-measurement scenario is envi-

sioned in which high-resolution, optical, thematic mappers and synthetic aperture radars, which have limited coverage, slow temporal repeat, and high data rates, are complemented by moderate-resolution (10 to 1 km) LSA radiometers, which provide full Earth coverage (large swaths) with fast temporal repeats (1 to 3 days) at modest data rates.

III. RADIOMETER ORBIT REQUIREMENTS FOR LARGE SPACE ANTENNAS

Orbit Altitude

Selecting the operating altitude for an LSA Earth radiometer is a rather complex task. The LSA spacecraft must be high enough to insure long experiment lifetimes with the required geographical coverage and yet low enough to satisfy spatial-resolution requirements with the smallest possible antenna. The factors affecting the choice of altitude and their impact on the space-observation system are listed in table 4.

TABLE 4.- FACTORS AFFECTING CHOICE OF ORBIT ALTITUDE

Measurement	Requirement	Impact on space-observation system
Experiment lifetime (orbit-mission duration)	Several years	$C_D A/m$; drag makeup capability
Spatial resolution	10 to 1 km	λ and D (for single beam)
Line of sight; local vertical incidence	<30°	Single polarization
Repeat intervals	3 days and 1 day	Swath-width choice; FOV; scanning or multiple-beam design
Global contiguous coverage	Full and partial	
Resolution-element distortion due to Earth's curvature and associated with large FOV's	Tolerance after corrections, ±5 percent	Design or data reduction

The angular-resolution requirement θ_r for an LSA in terms of the required spatial resolution or footprint F at the Earth's surface and the orbit altitude h is given as $\theta_r = 2 \tan^{-1} F/2h$ which, for small angles, is $\theta_r(\text{radians}) \approx F/h$. The limiting angular-resolution capability (see section IV) of a circular antenna of diameter D and operating wavelength λ is $\theta_c(\text{radians}) = 1.22\lambda/D$. Consequently, to meet the requirement means that $h \leq FD/1.22\lambda$. For a single-beam 200-m LSA sensing a measurand at $\lambda = 20$ cm (e.g., soil moisture) with the 10-km mandatory resolution, a radiometer must be operated in low Earth orbit (LEO) at altitudes less than approximately 8000 km. Operation at geosynchronous Earth orbit (GEO) is prohibited under the imposed constraints. Similarly, for a single-beam 50-m LSA sensing soil

moisture at $\lambda = 20$ cm with 1-km resolution, the orbit altitude must be less than approximately 200 km. Therefore, 200 km is considered to be the absolute minimum orbit altitude.

The required orbit lifetime is set by those applications which require long-duration measurements, such as climate prediction. The ballistic coefficient C_DA/m of the spacecraft affects the orbit lifetime and, thus, establishes a practical lower limit on orbit altitudes, as illustrated in figure 1 (from ref. 9). The calculations are for a period of low solar activity which gives long lifetime estimates. The C_DA/m ratio for a large-aperture microwave-radiometer spacecraft will probably be in the range from 0.02 to 2, depending on the configuration. (See ref. 10.) Orbits as low as 450 km may have lifetimes up to 4 yr without any significant orbit-boost-adjustment capability. Therefore, for a lifetime requirement of several years, 450 km is considered to be the lowest practical orbit altitude.

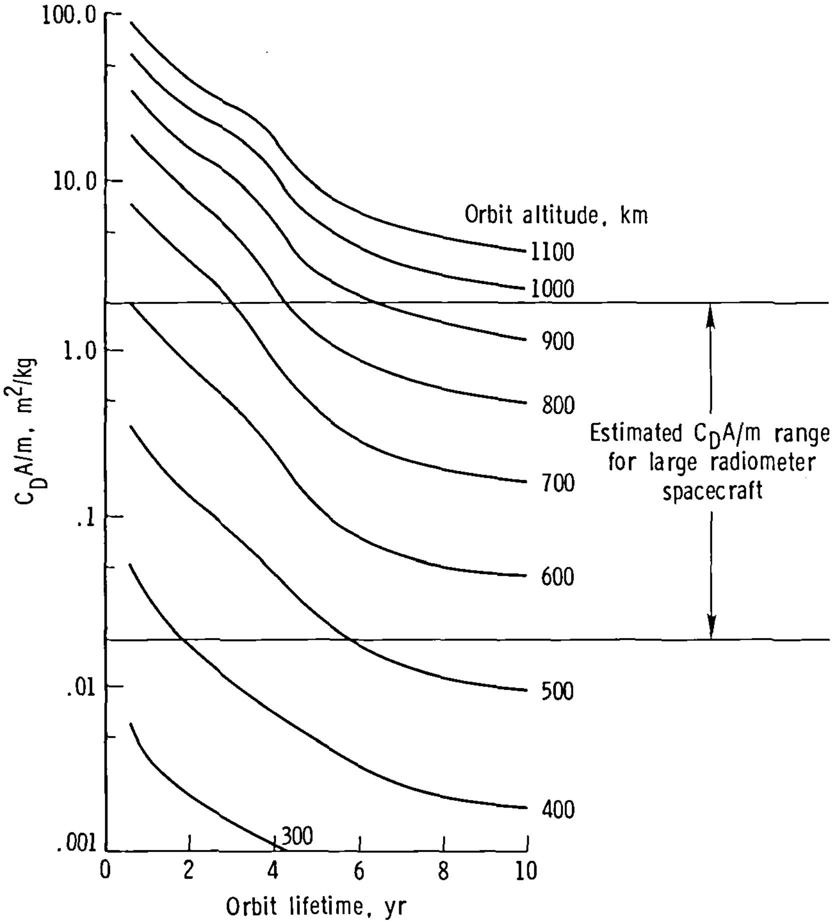


Figure 1.- Lifetimes in low Earth orbit for periods of low solar activity. Adapted from reference 9.

In section II, the need was established for contiguous coverage (implying wide swaths) with repeat intervals of 1 to 3 days. Wide swaths at low altitudes require large system fields of view and large incidence angles of the radiometer line of sight with the local vertical direction at the Earth's surface. In the discussion of polarization requirements (section IV), it is established that single, horizontal

polarization sensing is sufficient to make the desired soil-moisture measurements, provided the incidence angle does not exceed approximately 30°. By imposing this 30° constraint, the minimum altitude for contiguous coverage with a 1-day repeat interval is approximately 2200 km. Such an altitude penalty, five times the practical minimum, is probably not acceptable since it means that the antenna diameter D must increase five times to achieve the required spatial resolution. In order to show the impact of lower altitude alternatives on the space-observation system, table 5 lists the approximate viewing parameters for several examples. The reference example is the higher-altitude orbit discussed previously.

TABLE 5.- APPROXIMATE VIEWING PARAMETERS FOR GLOBAL CONTIGUOUS COVERAGE

Example	Altitude, km	Incidence angle, deg	Orbits, number per day	Repeat interval, days	Swath width		System FOV, deg
					Width, deg longitude at equator	Width, km	
Reference	2200	30	11	1	17	2000	43
1	450	30	15	3	4	500	56
2	450	60	15	1	12	1500	108

In example 1, the need for measurements with a 1-day repeat interval is ignored, which results in being able to operate as low as 450 km, thus reducing the swath width and mildly increasing the field-of-view angle.

In example 2, the incidence-angle limit of approximately 30° for single polarization is ignored, which also results in being able to operate as low as 450 km. The swath width required is somewhat smaller than that of the reference example because more viewing opportunities (i.e., orbits per day) occur at the lower altitude. The system sacrifices are the probable need for dual-polarization sensing and the use of very large system FOV's.

Earth-curvature effects over wide swaths distort the "footprint"; likewise, systems with a large field-of-view angle have inherent distortions. The LSA design and/or the data-reduction algorithms must correct such distortions to within tolerances. (See table 4.) After field-of-view and swath-width design choices are made, the final part of the orbit-altitude selection process determines the exact fractional number of orbit repetitions per day Q required to fix exactly the revisit times and to guarantee proper swath-pattern overlap margins. Figure 2 (adapted from ref. 11) gives the orbit altitude h necessary to achieve the specified orbit-repetition factors Q. For example, for 1-day repeats with values of Q of 15 and 14, the corresponding altitudes are approximately 540 and 850 km, respectively. For 3-day repeats with values of Q of $15\frac{1}{3}$, $14\frac{2}{3}$, $14\frac{1}{3}$, and $13\frac{2}{3}$, the altitudes are approximately 460, 640, 775, and 975 km, respectively.

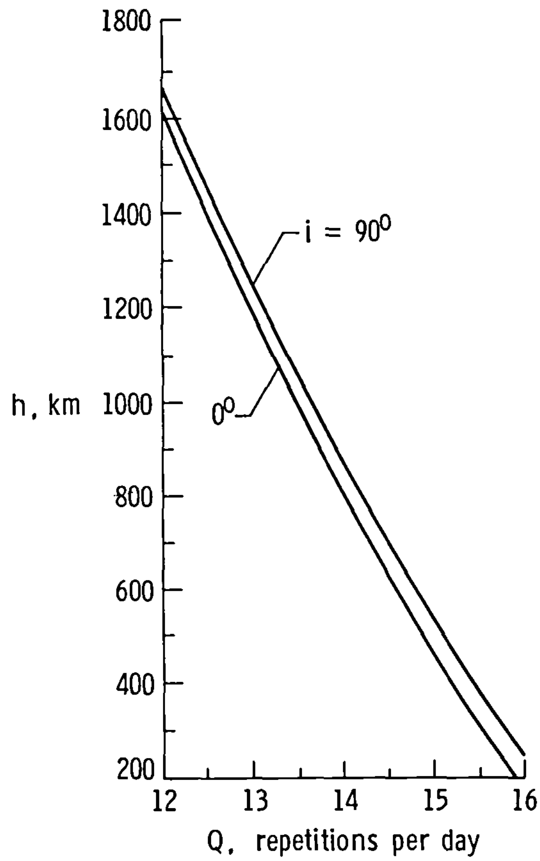


Figure 2.- Orbit altitude plotted against orbit-repetition rate. Adapted from reference 11.

In summary (see table 6), altitude choices are determined by different requirements and three altitudes are possible: (1) a very-high-orbit range from 2200 to 8000 km, where useful measurements can potentially be made with single polarization, but for which larger antenna apertures are required for spatial resolution; (2) a very-low-orbit range from 200 to 450 km, where the drag-makeup capability necessary for long experiment lifetimes is a significant design consideration (this range is usually reserved for proof testing onboard Shuttle sortie missions); and (3) an intermediate orbit-altitude range from 450 to 2200 km, where long life can be obtained more easily and where some trade-offs regarding resolution, field-of-view angles, swath width, spacecraft drag, and so forth, are possible. Finally, within each altitude range, the repeat-interval requirements dictate a selection from several discrete altitudes and, generally, the lowest altitude is selected to obtain better spatial resolution with a smaller aperture. For example, the lowest altitude in the intermediate range for a 3-day repeat ($Q = 15\frac{1}{3}$ repetitions per day) is approximately 460 km, and the lowest altitude for a 1-day repeat is approximately 540 km.

TABLE 6.- ORBIT ALTITUDE

Altitude descriptor	Requirement
Maximum: 8000 km	Single-beam resolution[a] of 10 km with 200-m aperture at $\lambda = 20$ cm
Minima:	
200 km	Single-beam resolution[a] of 1 km with 50-m aperture at $\lambda = 20$ cm
450 km	Lowest practical long-lifetime orbit
2200 km	Lowest orbit for global contiguous sensing with 1-day repeat using incidence angles <30°
Practical operating and design trade-offs range from 450 to 2200 km	Long-duration, high-resolution, global coverage with smallest antenna

[a]Resolution is based on a beamwidth of approximately 3 dB.

Orbit Inclination

Orbit inclination i has a small effect on altitude selections for given repeat intervals (see fig. 2), with the greatest effect being on geographic coverage. Polar coverage is lost with low-inclination orbits, whereas equatorial coverage is enhanced by a factor of $1/\sin i$. Orbit inclinations in the range from 60° to 98° can best satisfy the geographic-coverage requirements. The higher inclinations may be chosen for better ice coverage. A Sun-synchronous orbit (98° inclination) may be chosen so that measurements can be made at the same time of day and/or to reduce Sun-glint interference with the relatively weak microwave emission. An orbit inclination of 60° provides good coverage over the temperate zones and farm belts and, consequently, is about the lowest orbit inclination that can satisfy the coverage required for soil-moisture and sea-surface-temperature measurements.

For an orbit inclination of 60° at an altitude adjusted for a 1-day repeat interval (approximately 600 km), the continental United States (CONUS) portion of a coverage plot is shown in figure 3 (from ref. 10) for a radiometer with a 300-km swath. Approximately 20 percent of full coverage is obtained. If longer repeat intervals are acceptable, the extra orbit passes during the interval can fill in the pattern. With the same 60° orbit inclination and 300-km swath and a minor altitude adjustment to provide a 3-day repeat, approximately 60 percent of full CONUS coverage is obtained. If the swath is increased to approximately 500 km, full CONUS coverage is possible. The feasibility of meeting the requirement of contiguous coverage of the United States and other major geographic areas vital to the various measurements, with a repeat interval approaching 1 to 3 days, is impossible to assess at this point for it will depend on the particular radiometer spacecraft design and the corresponding orbit parameters. In particular, designs for wide-angle off-nadir viewing and for low atmospheric drag must be developed for systems whose resolution performance may depart significantly from the ideal diffraction-limited case. Such system implications and limitations are addressed in the succeeding sections.

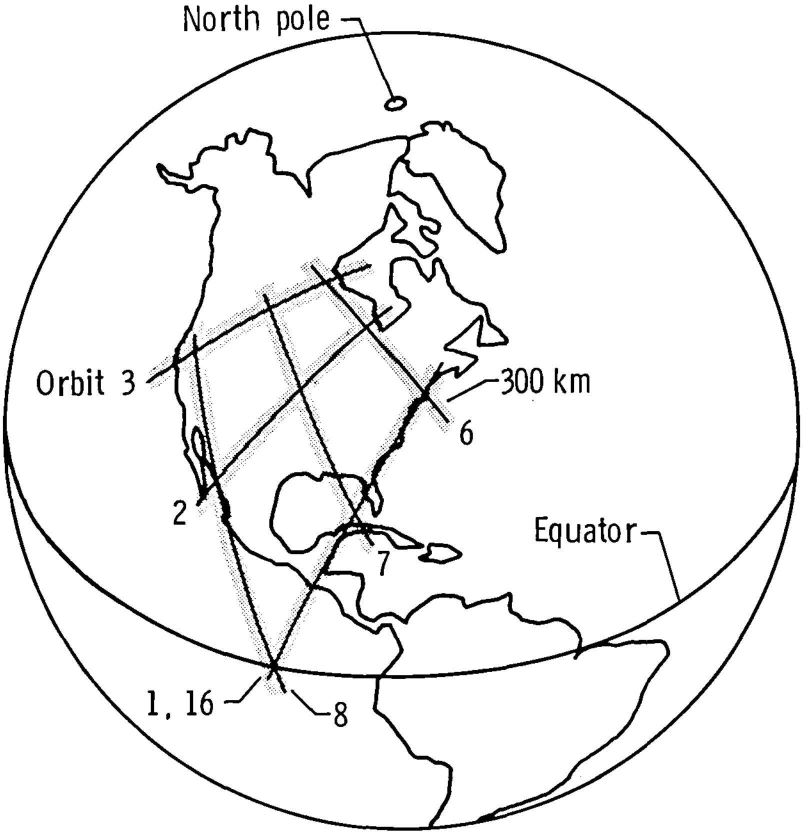


Figure 3.- Geographic coverage for 1-day-orbit repeat interval at altitude of approximately 600 km. Adapted from reference 10.

Orbit Maintenance

Since orbit-inclination variations are small and Earth measurements are relatively insensitive to such variations, orbit maintenance is primarily concerned with altitude maintenance. Orbit-altitude changes affect the spatial resolution, swath width, geographic coverage, and sampling repetition. Orbit-altitude changes are caused by the atmospheric drag of the spacecraft and by solar-radiation pressure on the spacecraft. For example, at 900 km, by using conservative estimates of antenna size, mass, cross-sectional area, and atmospheric density (solar-cycle maximum), the atmospheric drag of a sample spacecraft is estimated and average orbit-altitude decay is calculated. (See fig. 4.) This decay is relatively smooth if compared with the cyclic fluctuations in the perigee, which is also shown in figure 4. The cyclic fluctuations are the result of the integrated action of atmospheric-density (drag-force) variations with time, gravitational forces of the Earth, Sun, and Moon, solar-radiation pressure, and magnetic forces on the spacecraft. Even for large spacecraft with large area mass ratios required for LSA radiometry, the cyclic fluctuations are small if compared with the steady-state decay of average orbit altitude.

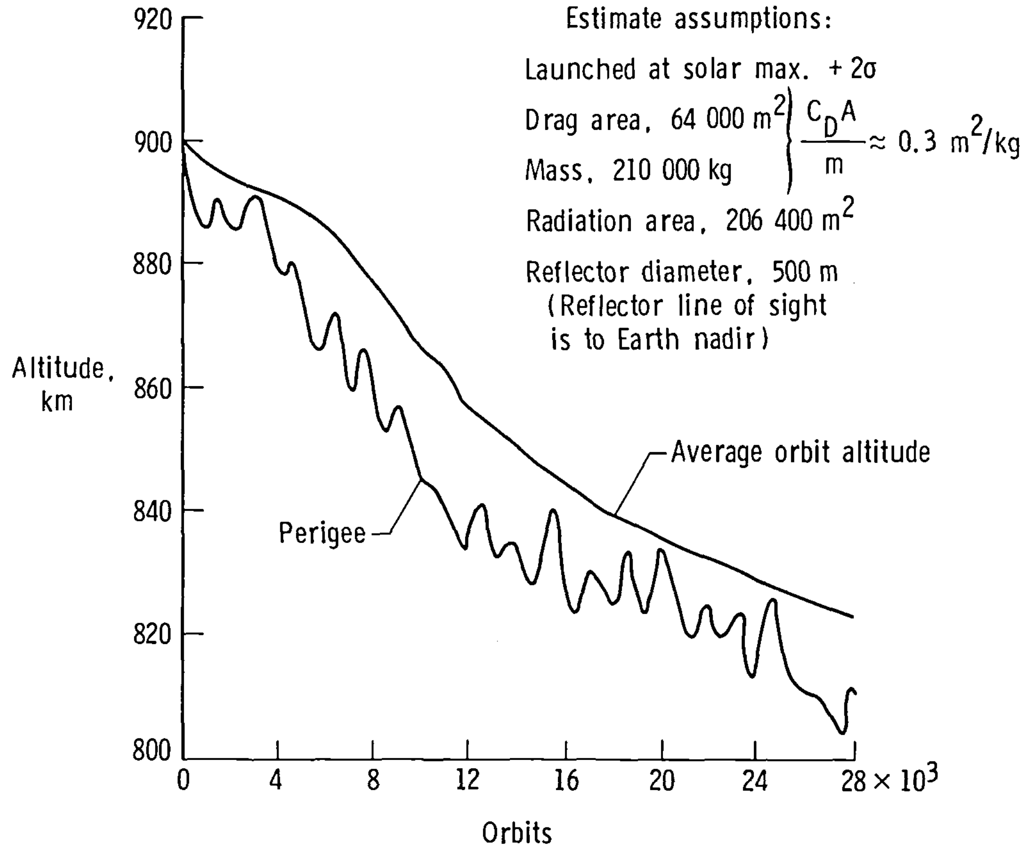


Figure 4.- Sample estimate of orbit-altitude variations and decay. Adapted from reference 10.

It is difficult, costly, and not necessary to compensate for the cyclic fluctuations in orbit altitude, but the steady decline in average altitude cannot be ignored for long-lifetime missions. Changes in the sampling pattern and repeat interval are associated with loss of orbit altitude. At some point in the process of acquisition, analysis, and interpretation of the desired data, most users of microwave-radiometer data either map or synthesize images of the measured quantities. In addition to good image quality and accurate geodetic registration, microwave-radiometer data users must be guaranteed that a particular orbit pass will occur with some degree of precision over the programmed area and at the programmed time. This is especially important in planning operations to acquire data at specific times and specific sites. Requirements for the precision have not yet been set by microwave-radiometer data users, but tolerances have been estimated by comparing LSA missions with other Earth-observation missions. Approximate tolerances which appear to be easy to meet are expressed as follows:

Lateral drift of orbit	< ±0.1 swath width or five times the resolution element size, whichever is smaller
Sampling-time drift	< ±15 min for Sun-synchronous orbit; < ±1 hr for 60° orbit

For a particular spacecraft design, these tolerances can be translated into propulsion-system performance requirements and onboard propellant needs.

Summary of Orbit Requirements

Most LSA observation requirements can be satisfied by operating within the altitude range from 450 to 2200 km. In this range, many design trade-offs are possible. Discrete altitude selections are associated with the orbit-repetition rate and the revisit-interval requirements. For example, approximately 460 km is the lowest altitude for a $15\frac{1}{3}$ orbit-repetition rate required for a 3-day repeat cycle.

Coverage of important farm belts and ocean areas dictates an orbit-inclination choice >60°. Ice coverage may demand near-polar orbits. The Sun-synchronous 98° orbit may be chosen for single time-of-day sampling and avoidance of Sun glint.

Active maintenance of average orbit altitude may be required in some orbits to retain initial sampling repeat cycles, swath, contiguity, and geodetic precision of mapped-data products.

IV. RADIOMETRIC REQUIREMENTS FOR LARGE SPACE ANTENNAS

Earth-observation requirements were defined in section II and orbit requirements were defined in section III for LSA space-flight missions. This section summarizes the resulting requirements imposed on the LSA radiometer system itself. These include requirements for frequency, polarization, spatial resolution (including the effects of beam efficiency and aperture size), brightness-temperature range, accuracy, and temporal resolution (including the effects of predetection bandwidth, system noise, and integration time).

Frequency

The selection of the optimum operating frequency for the LSA microwave radiometer requires consideration of the following five factors:

(1) The sensitivity of the radiometric brightness temperature T_B to a change in the geophysical parameter to be measured varies with frequency; the magnitude of the partial derivative of brightness temperature with respect to the geophysical parameter is frequency dependent. Examples of the sensitivity of T_B to changes in sea-surface temperature (SST) and sea-surface salinity are presented in figures 5 and 6, respectively. The measurement of open-ocean SST (salinity is 36 ppt) over a temperature range from 0°C to 30°C with a reasonable sensitivity of 0.25 K/°C or better (higher) limit the frequency range from 3.3 to 6.2 GHz for an incidence angle of 0° (nadir) and from 2.6 to 8.3 GHz for an incidence angle of 53° (with vertical polarization). The choice of a higher sensitivity factor would reduce the available frequency range, whereas choosing a lower sensitivity factor would increase the radiometer-accuracy requirement. The measurement of salinity with a reasonable

sensitivity of 0.25 K/ppt for open oceans at 20°C would require a frequency less than 2.2 GHz for an incidence angle of 0° and less than 2.8 GHz for an incidence angle of 53°.

The variation of the microwave brightness temperature of the sea surface is a function of thermodynamic temperature (SST), dielectric constant (temperature and salinity), surface roughness (wind speed, direction, and fetch), and surface coverage (foam, oil, and streaks). The retrieval of one of the aforementioned geophysical parameters requires either a knowledge of the other geophysical parameters, that is, an independent measurement of the geophysical parameter, or the selection of a frequency at which the sensitivity of brightness temperature to that parameter is small. For example, if a frequency of 8 GHz and an incidence angle of 53° were chosen to measure the SST, the effect of salinity would be -0.02 K/ppt. Since, from figure 5, temperature sensitivity is 0.27 K/°C at 0°C, then the error sensitivity due to salinity would be -0.02°C/ppt. This error source could be neglected for an accuracy requirement of ±1°C.

The sensitivity of microwave brightness temperature of the sea surface to wind speed is shown in figures 7(a) and 7(b) for several models and theories. (See refs. 12 and 13, respectively.) The sensitivity to wind speed increases with frequency and is a function of polarization and incidence angle. There is an incidence angle (≈50°) at which the sensitivity to surface roughness due to wind speed for vertical polarization is minimized. (See ref. 14.) However, the effect of foam coverage is still present. From figure 7(a), if 8 GHz were chosen to minimize salinity effects, the sensitivity to wind speed would be 1.1 K/m/sec. If a sensitivity of 0.25 K/°C is assumed, this would translate to an SST error sensitivity of 4°C/m/sec, which is highly significant for an accuracy requirement of ±1°C. The present capability of remote sensing of wind speed is 1.3 m/sec (or 1σ) for the Seasat SASS and 2 m/sec for the Seasat SMMR. (See ref. 15.)

(2) Atmospheric losses as a function of frequency limit the measurement of the geophysical parameters of the Earth's surface to microwave frequencies below approximately 40 GHz. (See ref. 12.)

(3) Galactic and cosmic noise reflected from the Earth's surface constitute a limiting lower frequency. The cosmic noise contributes a constant background noise of 3 K over the frequency range of interest. However, at 1 GHz, galactic noise varies between approximately 5 and 50 K, depending upon location of the zenith point of the observation point of the Earth's surface in the celestial sphere. Below 1 GHz, galactic noise increases with frequency between $f^{-2.5}$ and $f^{-3.0}$, dependent upon the location of the zenith point. (See ref. 4.) Therefore, operation of microwave radiometers for LSA applications is not as accurate below 1 GHz because of the difficulty of making galactic-noise corrections.

(4) Radio-frequency interference (RFI) produces problems with proper operation of passive microwave sensors. As a result, the World Administrative Radio Conference

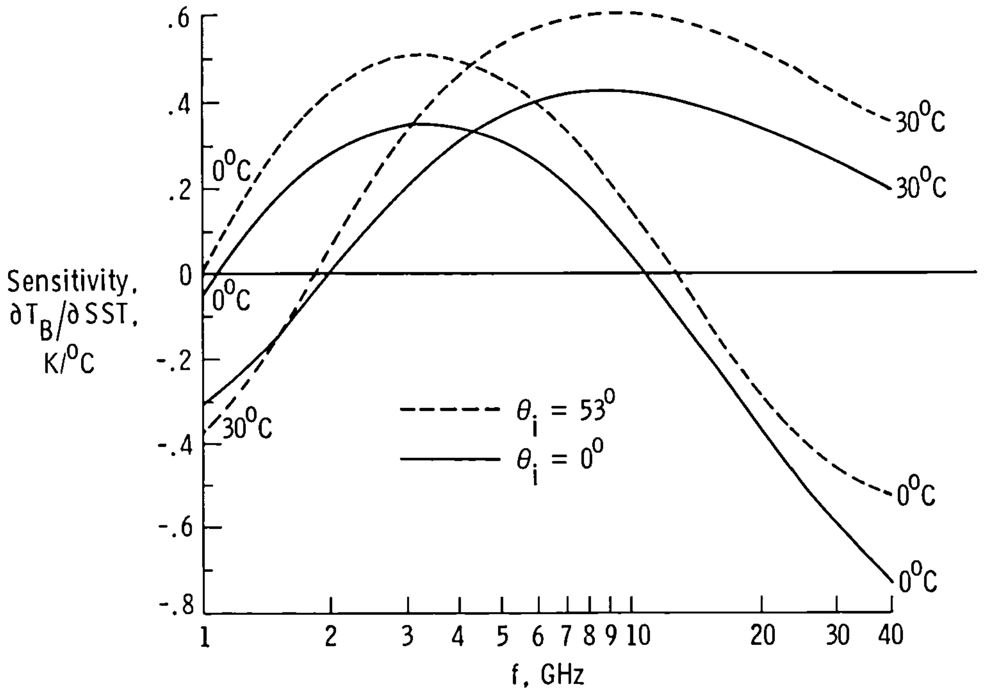


Figure 5.- Sensitivity of microwave brightness temperature of sea surface to variation in sea-surface temperature as a function of frequency, incidence angle (0° and 53°), and thermodynamic temperature (0°C and 30°C). Salinity, 36 ppt.

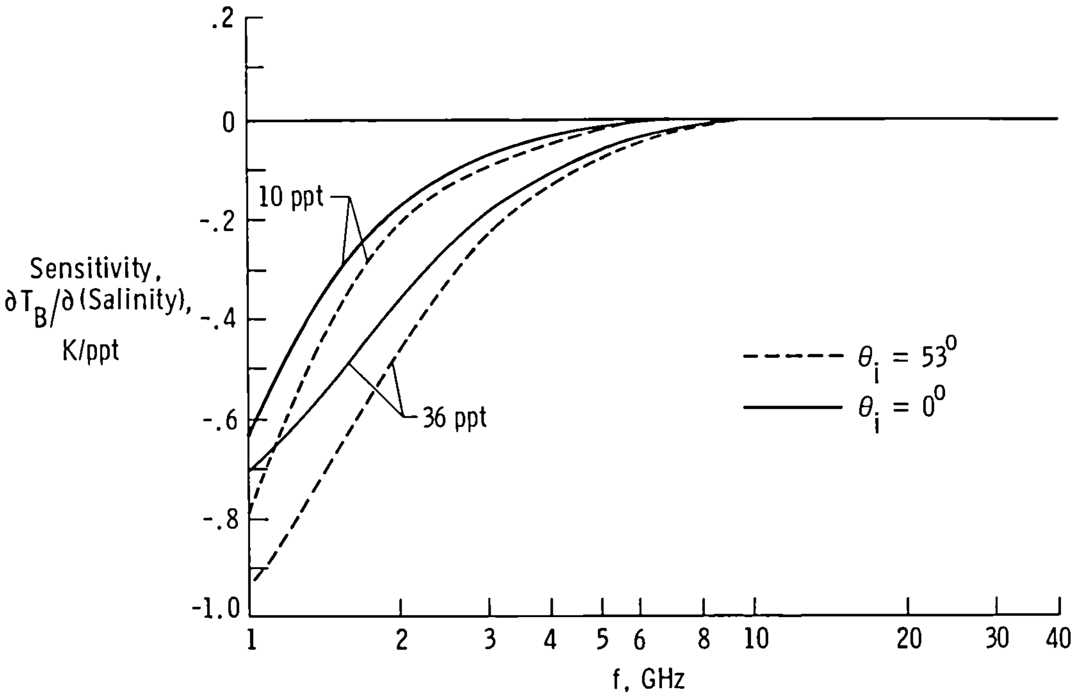
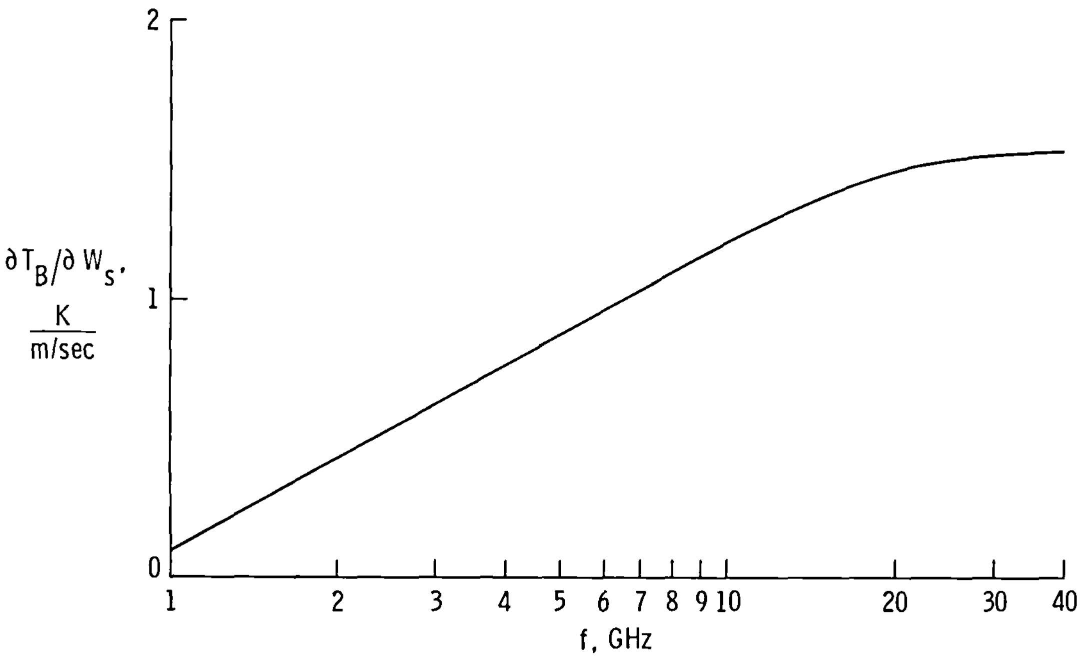
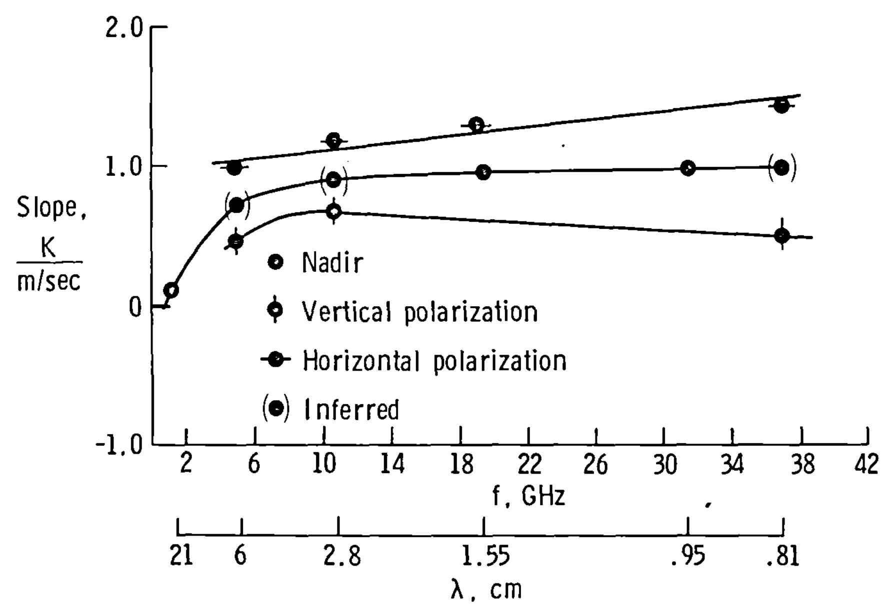


Figure 6.- Sensitivity of microwave brightness temperature of sea surface to variation in salinity as a function of frequency, incidence angle (0° and 53°), and salinity (10 ppt and 36 ppt). SST = 20°C.



(a) Data compiled from experimental data without specification of incidence angle and polarization. Adapted from reference 12.



(b) Data showing effects of incidence angle and polarization. (Inferred value of nadir data obtained by averaging horizontal and vertical measurements.) Adapted from reference 13.

Figure 7.- Sensitivity of microwave brightness temperature of sea surface to wind speed.

(WARC) has allocated several frequency bands, classified as either primary, shared, or secondary, for passive microwave measurements from space. These frequency bands are listed in table 7.

TABLE 7.- WARC FREQUENCY ALLOCATIONS

Frequency range, GHz	Type of allocation	Measurand*
1.370 to 1.400	Secondary	a
1.400 to 1.427	Primary	a
2.640 to 2.655	Secondary	b
2.655 to 2.690	Shared	b
2.690 to 2.700	Primary	b
4.200 to 4.400	Secondary	b
4.950 to 4.990	Secondary	b
6.425 to 7.075	Shared	b, c
7.075 to 7.250	Shared	b, c
10.600 to 10.680	Shared	c
10.680 to 10.700	Primary	c
15.200 to 15.350	Secondary	c, d
15.350 to 15.400	Primary	c, d
18.600 to 18.800	Shared	d
22.210 to 22.500	Shared	d
23.600 to 24.000	Primary	d
31.300 to 31.500	Primary	e
31.500 to 31.800	Primary	e

*Measurands are indicated by the following letters:
a: Salinity; soil moisture
b: Sea-surface temperature
c: Water roughness (winds); rain; ice; snow
d: Rain; ice; snow; water vapor
e: Ice; oil spills; clouds; snow

Primary allocations are those in which all electromagnetic emissions by other services are prohibited by international agreement. Shared allocations are those where other emissions are permitted; however, other users are requested to limit emissions to those levels which would allow operation of passive spaceborne sensors. Secondary allocations are those where the passive sensor cannot place any constraints on emissions by other services. When referring to table 7, it is apparent that there are very few protected frequency bands available for passive remote sensing from Earth-orbiting satellites. The avoidance of RFI will be a key factor in the overall frequency selection since shared and secondary allocations must be used.

The problem of RFI can easily be shown. For example, the relationship between antenna temperature T_{ant} and the power level at the antenna P is given by

$$P = kTB$$

where k (the Boltzmann constant) is equal to 1.38×10^{-23} W-K^{-1}-Hz^{-1} and B (the predetection bandwidth) is equal to 200 MHz. For a signal level equivalent to a radiometer noise level of 0.2 K, the power at the antenna terminals would be -123 dBm. Any external interference must be kept below this level. By assuming that the antenna was not pointed toward the interfering signal, a spatial filtering by the antenna of at least 30 dB can be used. By assuming that a maximum-size antenna of 200 m is used at a range of 1000 km with an aperture efficiency of 50 percent, the effective isotropic radiated power (EIRP) from the ground can be calculated from

$$\text{EIRP} = 5.0 \times 10^{-10} \text{ mW} \times \frac{2\pi(10^6)^2}{\frac{\pi}{2}(100)^2} = 0.2 \text{ mW}$$

That is, an isotropic radiator that transmits 0.2 mW into the side lobes on the surface of the Earth would barely be detectable. Any higher power would require filtering in the radiometer.

The measurement of the various geophysical parameters can be made only in specific frequency regions. As stated previously, sea-surface temperature can be measured accurately only between 2.6 and 8.3 GHz. Consideration of RFI and frequency allocation would limit the selection of a frequency for sea-surface-temperature measurement to a 60-MHz-wide band from 2.64 to 2.70 GHz, a 200-MHz-wide band from 4.2 to 4.4 GHz, a 40-MHz-wide band from 4.95 to 4.99 GHz, or an 825-MHz-wide band from 6.42 to 7.250 GHz.

(5) The selection of a frequency for microwave-radiometer measurement of soil moisture is influenced by an additional factor, the depth of penetration through the biomass cover, such as vegetation, to the Earth's surface to measure the soil-moisture content. The correlation coefficient of the measured brightness temperature with volumetric soil-moisture content as a function of frequency is shown in figure 8 (data taken from ref. 16). The measurement of soil moisture for bare soils can be made at any frequency between 0.5 and 10 GHz. However, if the surface is covered by vegetation, then only the longer wavelengths can provide the depth of penetration necessary to measure soil moisture. Consideration of frequency allocation, RFI, galactic noise, and depth of penetration limits the frequency for soil moisture to a 57-MHz-wide band from 1.370 to 1.427 GHz. This also represents a good frequency selection for salinity measurements in the open ocean.

In summary, the overall frequency range for Earth-viewing LSA radiometers is roughly bounded at the lower end by galactic noise and at the higher end by atmospheric losses. The range selected for this requirements definition is 1 to 40 GHz. Individual frequency selections from within this range for each measurand must be made very carefully by taking into account the five factors discussed and the fact that an LSA radiometer, from a practical standpoint, probably will not be designed for an individual optimized frequency for each measurand. Instead, two to six frequencies may have to suffice for all measurands. For this requirements definition,

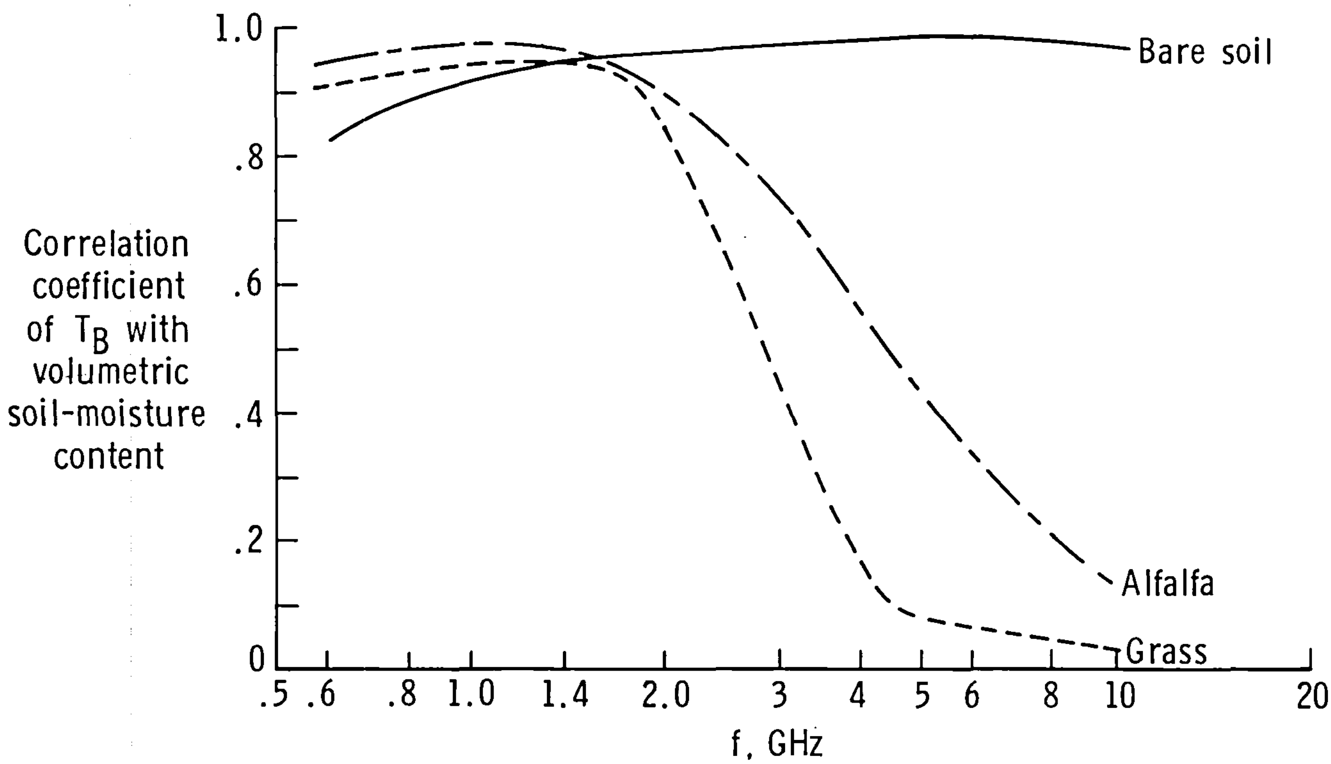


Figure 8.- Correlation of microwave brightness temperature with volumetric soil-moisture content for bare soil, grass-covered soil, and alfalfa-covered soil as a function of frequency. Adapted from reference 16.

the practical frequency (and wavelength) ranges from which frequencies can be selected are listed in table 8. Also listed are the selections for a sample six-frequency radiometer.

TABLE 8.- PRACTICAL FREQUENCY AND WAVELENGTH RANGES OF MEASURANDS

Frequency wavelength	Soil moisture	Sea-surface temperature	Salinity	Water roughness (winds)	Ice	Water pollutants (oil)	Atmospheric water vapor	Precipitating liquid water (rain)	Nonprecipitating liquid water (clouds)
Frequency range, GHz	1 to 10	2 to 6	1 to 2	2 to 37	10 to 37	1 to 37	15 to 25	6 to 37	20 to 37
Wavelength, cm ...	30 to 3	15 to 5	30 to 15	15 to 0.8	3 to 0.8	30 to 0.8	2 to 1.2	5 to 0.8	1.5 to 0.8
Sample frequency selections, GHz:									
1.4	Critical		Critical		Helpful	Helpful			
4.2 to 4.4	Important	Critical		Helpful	Helpful	Helpful			
6.6	Important	Important		Important	Important	Helpful		Helpful	Important
10.7	Helpful	Helpful		Critical	Important	Helpful		Helpful	Important
21		Helpful			Important		Critical	Important	Helpful
37		Helpful			Critical	Important		Important	Critical

Polarization

Polarization of the antenna feed is important since the emissivity of the surface is a function of both the polarization angle and incidence angle of the sensing beam received by the LSA. The emissivity of the surface must be modeled so that antenna temperature can be converted to the physical temperature of the surface. The modeling is made easier if both the polarization angle and incidence angle are fixed. However, this is not always consistent with physically realizable antenna scanning and feed systems. Table 9 lists the polarization options.

TABLE 9.- POSSIBLE COMBINATIONS OF POLARIZATION IN ORDER OF DECREASING DESIRABILITY

Order of desirability	Linear polarization	Incidence angle	Comment
1	Dual	Fixed	Highly desirable
2	Single	Fixed	
3	Dual	Rotating	
4	Single	Rotating	Least desirable

The measurement of a specific geophysical parameter determines which polarization is desired. Soil-moisture measurements are more sensitive to horizontal polarization with incidence angles less than 30°, whereas sea-surface-temperature measurements are more sensitive to vertical polarization with incidence angles around 50°. (See ref. 14.) Circular polarization is not listed since measuring two orthogonal linear polarizations is equivalent to measuring circular polarization.

As noted in table 9, a fixed incidence angle with beam position is very desirable. This implies a conical scan or a conical array pattern of multiple beams. In the case of extremely wide swath systems necessary for the Earth's coverage, the incidence angle of the radiometer line of sight with the local vertical direction at the Earth's surface is not the same for all sensing beams, but the various angles are fixed by the viewing geometry. As noted in section III on radiometer orbit requirements, the imposition of a limit on the beam incidence angle can impose a severe altitude operating penalty.

Cross-polarization effects caused by the LSA itself, for example, offset feed, should be minimized. Initial studies (unpublished) indicate that a criterion of -60 to -70 dB appears to be quite adequate for measurand retrieval purposes; however, the capability of LSA designs to meet this requirement must be investigated. Present antenna designs indicate that this is an extremely difficult design criterion to meet.

Spatial Resolution

The remote-sensing data-user's requirement for spatial resolution given in table 3 as 10 km (mandatory) to approximately 1 km (desired) is interpreted in this section in terms of radiometer requirements. Unavoidable diffraction and scattering degrade remote-sensing beams; consequently, the spatial-resolution requirement must

be more precisely defined in both spatial size and energy distribution of the sensing beams. The paragraphs that follow show the need for precise requirements and develop the requirements related to beam efficiency, antenna aperture, and reflector surface roughness.

Spatial resolution has many different meanings. In image evaluation, resolution refers to the size of the smallest discernible feature. In radiometry, the Rayleigh criterion states that two components of equal intensity should be considered resolved when the principal maximum of one coincides with the first minimum of the other. In remote sensing of the Earth's parameters, a number of terms have been used to describe the resolution element: for example, pixel, footprint, field of view (FOV), instantaneous field of view (IFOV), beam width, and spot size. For the purposes of this report, the resolution element is defined as the field of view at the Earth's surface during a single-measurement sequence.

In section III, the angular-resolution capability of a circular antenna of diameter D and operating wavelength λ was stated as $\theta_c(\text{radians}) = 1.22\lambda/D$, and this IFOV at the Earth's surface was considered the resolution element. The movement of the FOV during a measurement sequence is not taken into account. (The sequence is covered subsequently in section V in the discussion entitled "Sensitivity and Multiple Beams.") Furthermore, its characteristic dimension (in this case, a diameter) is defined by the 3-dB power contour of the main beam, even though the "edge" of the main beam is actually about 2.5 times larger. This resolution element disregarded part of the main beam, along with the side lobes and back lobes which together supply half the power received. Obviously, therefore, precision radiometry requires a knowledge of both the size and the energy of the full-sensing beam.

Beam efficiency.- Beam efficiency ε, or, more properly, main-beam efficiency, is defined as the integral of power over the main beam out to the first minimum divided by the integral over the complete antenna pattern. It represents the fraction of the power received through the main beam if the antenna was in an isothermal enclosure. The power received from all angles other than the main beam, $1 - \varepsilon$, comes from sources other than the scene being observed and, in general, is not accurately known. The effective antenna temperature then consists of two parts:

$$T_{ant} \approx \varepsilon T_{scene} + (1 - \varepsilon)T_{other}$$

The second term must be removed by assuming a temperature distribution for T_{other} and integrating over all the side lobes and back lobes. This process is simple if most of the power is in the first side lobe and the scene is homogeneous, such as an ocean scene. On the other hand, the main beam may be on the ocean and the side lobes may be partially viewing land. In this case, it may be impossible to make the correction to the required accuracy. In any case, the larger the beam efficiency, the easier it is to correct for the unwanted received radiation. If, for example, $1 - \varepsilon = 0.02$ (a main-beam efficiency of 98 percent), the maximum value of the second term would be $0.02 \times 300° = 6°$, which could be calculated to within $\pm 0.2°$ with a knowledge of T_{other} to within $\pm 10°$.

The required beam efficiency is highly dependent on the required measurement accuracy, side-lobe structure, and scene heterogeneity. Experience in using data from the Seasat and Nimbus 6 SMMR has shown that for main-beam efficiencies less than 90 percent, it is difficult to correct for the power received from the side lobes and back lobes to the accuracy required for determination of sea-surface tempera-

tures. It is possible to obtain main-beam efficiencies ε of 99 percent with certain types of horn antennas to as low as 60 percent for a uniformly illuminated reflector antenna. Since the required main-beam efficiency is dependent on the particular observation, it is difficult to specify a general requirement on ε for a broad range of measurements other than to say that ε should be as high as possible. In order to provide guidance to designers and technologists, however, this requirements definition will adapt (to guarantee data inversion) $\varepsilon > 90$ percent for a homogeneous scene as a general requirement.

Beam size and antenna diameter.- In table 10, optical and microwave beams are compared with regard to radiation source, beam size, and beam efficiency for perfect

TABLE 10.- DIFFRACTION-LIMITED BEAMS

Radiation source	Case description	Beam size, rad	Beam efficiency, percent
Optical	Case 1: Incoherent; non-polarized; point source	$\approx 1.22\lambda/D$ to first minimum	84 (full Airy pattern)
	Case 2: Incoherent; non-polarized; extended source	$\approx 2.44\lambda/D$ to first minimum	84 (full Airy pattern)
Microwave	Case 3: Coherent; polarized point sources	$\approx 1.22\lambda/D$ to half-power points	50 (half-power beam)
	Case 4: Partially coherent; partially polarized; extended source	$\approx 3\lambda/D$	>90 (full main beam; side lobes depressed)

diffraction-limited designs. (Scattering of energy outside the main beam is covered next in the discussion entitled "Surface Roughness.") Case 1 is the classic optics case which uses the Rayleigh resolution criterion. The maximum possible energy in the main beam, called the Airy pattern, is 84 percent. (See ref. 17.) An extended source, case 2, however, applies more directly to remote sensing of the Earth with sensors such as those on Landsat. The 84-percent maximum energy occurs in the disk (or main beam) which is twice the classic optics size. (See ref. 18.) Case 3 applies to the traditional microwave-antenna half-power beamwidth used for communications, radar, and similar applications, whereas case 4 applies more directly to passive microwave remote sensing. In case 4, the effect of the side and back lobes must be suppressed in order to increase the main-beam efficiency to 90 percent or more. The size of this main beam is approximately 2.5 times the half-power size, or $3\lambda/D$.

In actual practice, the size of the resolution elements varies from the half-power beam size, approximately $1.22\lambda/D$, to twice the size of the main beam, $6\lambda/D$. (Twice the main-beam size allows for one beamwidth translation during a measurement sequence.) This ambiguity of approximately a factor of five exists in statements of both measurement requirements and measurement capabilities. In this requirements definition, therefore, a degree of conservatism is built in by using the criterion that the maximum dimension of the main beam should be equal to or smaller than one-

half the resolution requirement. By using this conservative criterion at the practical minimum altitude of 450 km, the antenna diameter D required for a 10-km resolution at λ = 20 cm is 54 m, whereas the best resolution possible with a 200-m antenna is 2.7 km.

Figure 9 shows the minimum required antenna diameter as a function of wavelength for a 600-km orbit. Both the optimistic and conservative criteria are used for the 10-km (mandatory) and the 1-km (desired) resolutions. For the mandatory 10-km resolution, the full 200-m aperture is not required for a single beam; but for the desired 1-km resolution, the 50-m aperture is adequate only at the upper end of the frequency range.

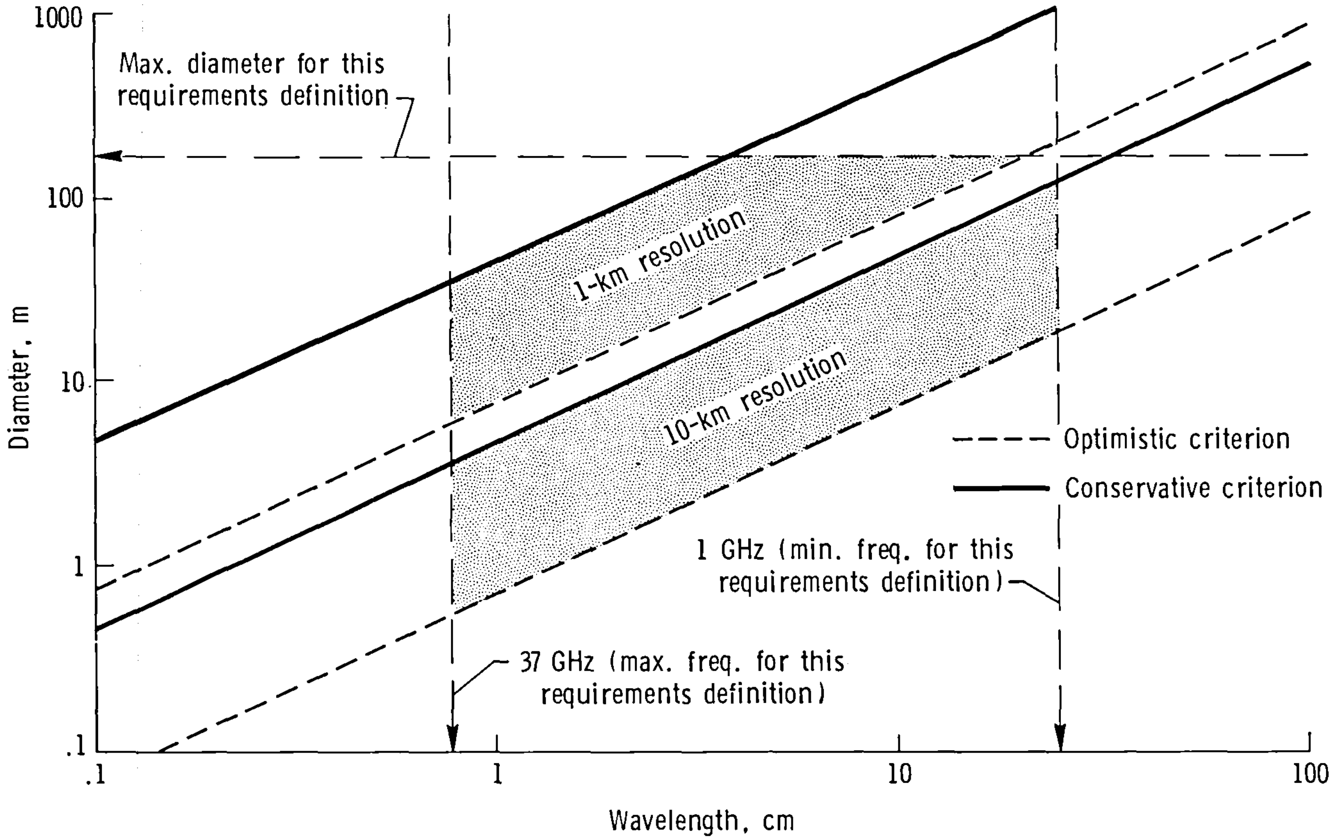


Figure 9.- Minimum required antenna diameter at orbit altitude of 600 km for various spatial-resolution requirements.

Surface Roughness.- In addition to diffraction, scattering from a reflector surface also reduces main-beam efficiency. That is, any deviation from a perfect geometric surface will scatter radiation out of the main beam. The direction in which the radiation is scattered is determined by the size and distribution of the errors. However, the magnitude of the energy gain of the main beam is given by the well-known Ruze formula $g = g_o e^{(-4\pi\delta/\lambda)^2}$. (See ref. 19.) Here, g_o is the gain for a perfectly smooth reflector and the exponential represents the energy attenuation factor due to the rms surface errors δ for a reflector operating at a wavelength λ; for example, if $\delta = \lambda/16$, beam efficiency is reduced to approximately

50 percent. If the beam efficiency must be greater than 90 percent and surface roughness is budgeted for only one-half of the 10-percent allowable beam-energy loss, then the surface irregularities must be maintained so that δ is less than $\lambda/55$.

The performance limits of large ground-based antennas used for radio astronomy and communications are determined primarily by the accuracy of the reflecting surfaces. Figure 10 plots antenna diameter as a function of minimum usable wavelength λ_{min} for some of the world's best radio telescopes. The criterion used for λ_{min}

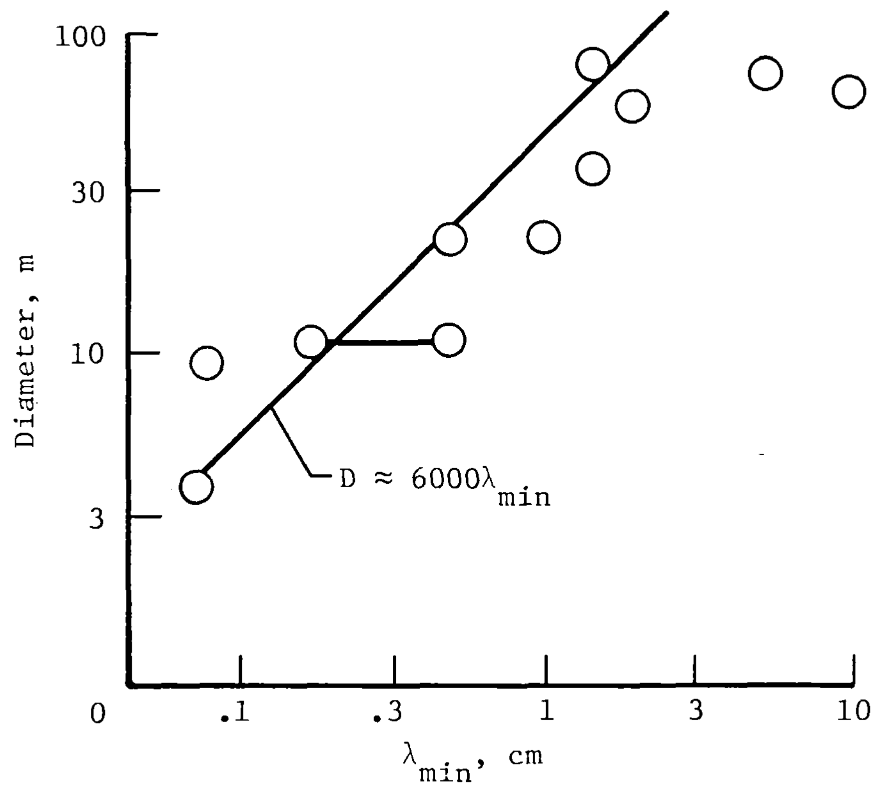


Figure 10.- Diameter plotted against operating wavelength for 10 Earth-based large antenna systems.

was the half-power antenna-gain criterion. It can be seen that there is a definite correlation between antenna diameter and λ_{min}. The solid line on the figure approximates the correlation and corresponds to $D \approx 6000\lambda_{min}$. By applying this correlation to LSA's at 37 GHz, the corresponding diameter is approximately 50 m. By using this criterion, antennas larger than 50 m would have to operate at less than 37 GHz. The half-power criterion used for radio telescopes corresponds to $\delta = \lambda/16$. If $\delta = \lambda/55$ is used as the criterion for Earth radiometry, high-frequency operation is further restricted. Alternative modes of operation are envisioned, however, where only a small portion of the total available aperture is used at the higher frequencies, or where the D/λ limit is raised by reducing δ through better engineering and manufacture of the reflecting surface and by the use of mechanically active surface controllers. Thus, the practical maximum operating frequency is somewhat dependent on configuration and technology, but 37 GHz remains as the requirement.

Brightness-Temperature Range, Accuracy, and Resolution

Earth-emitted radiation is the actual quantity sensed in the prescribed resolution element with a corresponding beam efficiency. It depends on both temperature and emissivity and is referred to as brightness temperature. The physical temperature over the Earth is approximately 290 ± 50 K. The emissivity varies from 1 to 0.2, thus giving a brightness-temperature range from 48 to 340 K. The cold (approximately 3 K) sky is often used as a calibration source so that the radiometers should have a dynamic range of approximately 3 to 340 K. The brightness-temperature ranges for the various measurands are shown in table 11. Also shown are the measurement accuracy and resolution requirements. The accuracy requirement, or, more properly,

TABLE 11.- BRIGHTNESS-TEMPERATURE RADIOMETER REQUIREMENTS

Geophysical parameter	Soil moisture	Sea-surface temperature	Salinity	Water roughness (winds)	Ice	Water pollutants (oil)
Brightness-temperature range, K ...	90 to 300	85 to 200	50 to 150	85 to 300	100 to 250	5 to 200
Brightness-temperature accuracy, K	2	0.2	0.2	1	2	(a)
Brightness-temperature resolution (precision), K	0.5	0.1	0.1	0.5	1	(a)

[a]To be determined.

the tolerance for uncorrected errors, varies drastically with the user's application. Generally, 1 percent of the brightness temperature or from 2 to 3 K is a typical requirement, but some specific applications require absolute accuracies that approach the precision and temperature resolution requirements.

The brightness-temperature resolution requirement is related to the accuracy and precision requirements for the measurands. It is often used interchangeably with radiometer sensitivity ΔT. However, in determining geophysical properties, for example, sea-surface temperature, the uncertainty in the measurement of brightness temperature is often larger than ΔT. (Radiometer calibrations include the same noise as the signal; consequently, the uncertainty in brightness temperature after calibration is larger than ΔT.) From unpublished data by William D. Stanley of

Old Dominion University, Norfolk, Virginia, the variance of the measurements can be modeled as

$$\sigma_{TA}^2 = C + \frac{(\Delta T)^2}{(1 + \alpha)^2 (1 - R_i)^2} \tag{1}$$

where

σ_{TA}^2 variance of antenna temperature for a desired measurand

C additive constant

α attenuation factor for radiometer front end

R_i power-reflection coefficient of input wave in forward direction

In this formulation, measurement uncertainties are related directly to ΔT, but other antenna and radiometer characteristics produce a multiplicative factor and an additive constant C. At low values of ΔT, generally <0.5 K, C becomes important. Values of C have been calculated by Stanley which, at small values of ΔT, increase variances by an order of magnitude or more. Based on these recent research results, the value chosen for ΔT as being reasonable for this requirements definition is 0.5 K.

V. SYSTEM-DESIGN IMPLICATIONS

In setting the requirements for LSA radiometers for the purpose of guiding technology developments, every possible effort was made to avoid constraining the system design. The goal was to set requirements boundaries within which trades could be made to effect viable, cost-effective, radiometer system designs. Nevertheless, the requirements do have system-design implications which, because of complex system interrelationships, may be difficult to assess. The hierarchy and interplay of the requirements is illustrated by the microwave-radiometer sensor-design diagram shown in block form in figure 11. Previous sections of this report have discussed most of the items summarized by this block diagram. For example, section II discussed the applications and measurements, section III related these to orbit requirements, and section IV dealt with the radiometer requirements. This section focuses on the system-design implications for the radiometer.

Antenna Losses and Radiometer Errors

Historically, actual measurement uncertainties for real-flight radiometers are often two to three times the preexperiment estimates. Accurate radiometers must minimize systematic error sources such as antenna side lobes, antenna-reflection coefficient, antenna loss, reflector-surface scattering, absorption and transmissivity, antenna physical-temperature variations, and antenna-pattern functions which can produce biases in the brightness temperature that are difficult to quantify or isolate. Random-error sources are related to various antenna losses and radiometer characteristics, including radiometer sensitivity ΔT, and are represented in the

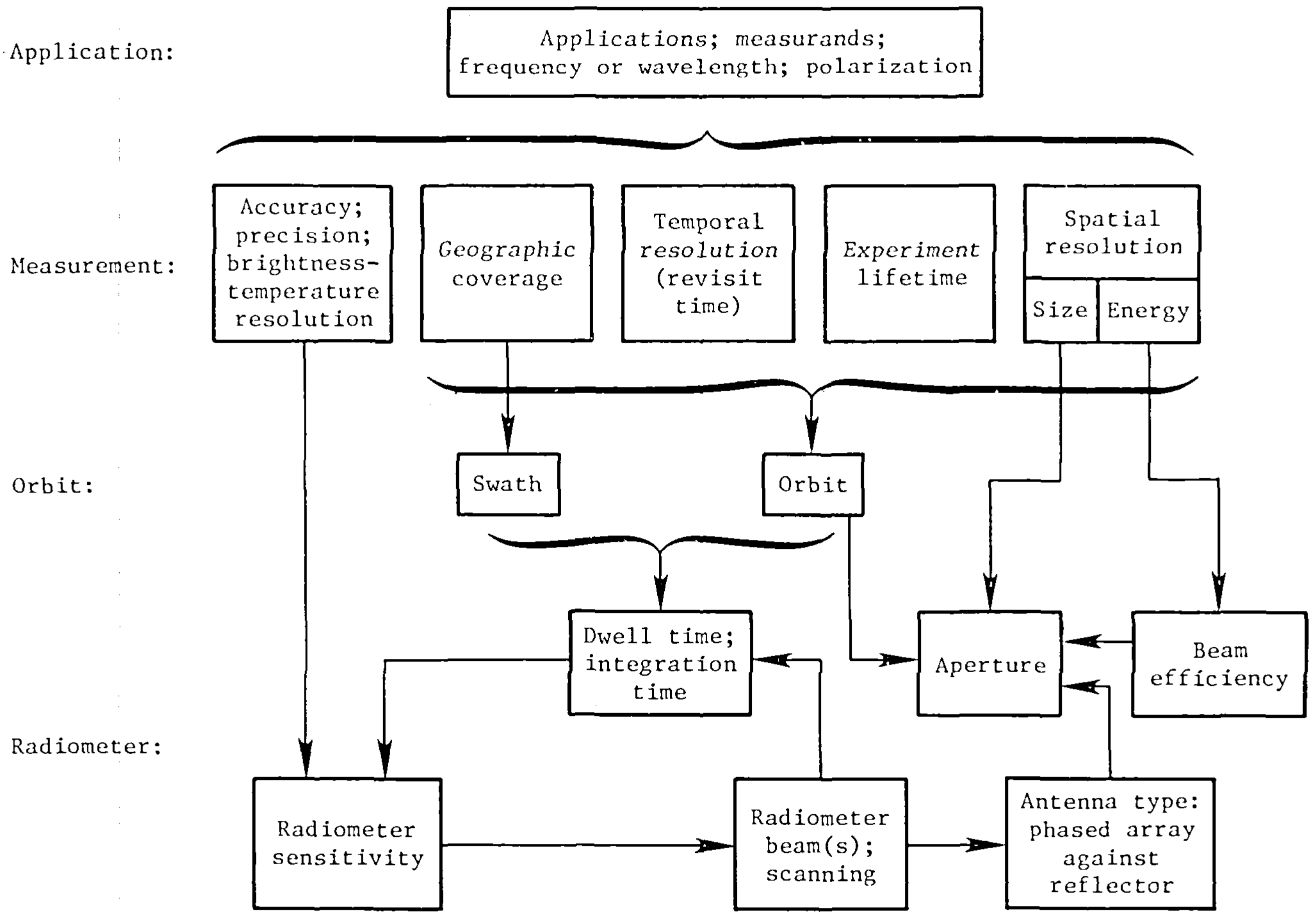


Figure 11.- Microwave-radiometer sensor-design diagram.

variance equation (eq. (1)) by the multiplicative factors and the additive constant C. *The system-design implications are that generic or particular LSA radiometer* designs must be analyzed in detail regarding potential antenna losses and radiometer errors and that calibration considerations must be an integral part of the design process.

Sensitivity and Multiple Beams

The temperature sensitivity of a switched radiometer can be modeled by

$$\Delta T = \frac{2T_{sys}}{\sqrt{B\tau}} \tag{2}$$

where

T_{sys} system noise temperature (received radiation plus internal noise)

B predetection bandwidth

τ postdetection integration time

As can be seen by equation (1), ΔT can be minimized by decreasing the system noise temperature or maximizing the bandwidth and/or integration time.

The system noise temperature T_{sys} is composed of the receiver temperature and the signal (antenna) temperature. For a precision null-balance Dicke radiometer,

$$T_{sys} = T_o + T_{rec} \tag{3}$$

where

T_o ambient temperature of reference load

T_{rec} receiver-input noise temperature

Here, T_o is typically 300 K and T_{rec} is generally the input noise temperature of the front-end, low-noise amplifier (field-effect transistor (FET) or parametric amplifier) and the preceding loss contribution.

The maximum allowable bandwidth is controlled by WARC frequency allocations; however, smaller bandwidths might be required to guard against interferences from adjacent bands. From 1 to 20 GHz, typical bandwidths range from 5 to 200 MHz, depending on the frequency of operation. Above 20 GHz, bandwidths typically are greater than 200 MHz.

In order to keep from smearing the measurement results, the integration time should be smaller or equal to the time that the sensing beam dwells on a resolution element. Most Earth-viewing microwave instruments (ESMR, SCAMS, SMMR, and MSU) use a crosstrack scan with continuous coverage within the scan limits; that is, the footprints are contiguous in both along-track and crosstrack directions. The observed region between the scan limits is called the swath. As the footprint is made smaller, the time available for a single measurement becomes shorter and the temperature radiometer sensitivity ΔT, consequently, degrades. With a single receiver instrument, there is always a trade-off between footprint size and sensitivity if complete surface coverage is maintained within each swath measurement zone.

It can be shown that the dwell time t_d (the time available for a single measurement) is given by

$$t_d = \frac{F^2}{SV} \tag{4}$$

where F is the footprint diameter, S is the edge-to-edge swath containing S/F individual footprints, and V is the orbit velocity (where Earth rotation is ignored).

By setting $t_d = \tau$ and using typical values in equations (2), (3), and (4), ΔT is calculated for footprints of 10 km and 1 km over a swath-width range from 100 to 2000 km. These results are plotted in figure 12. Also displayed are the measurement requirements for brightness-temperature resolution from table 10 and swath-width requirements for various types of coverage.

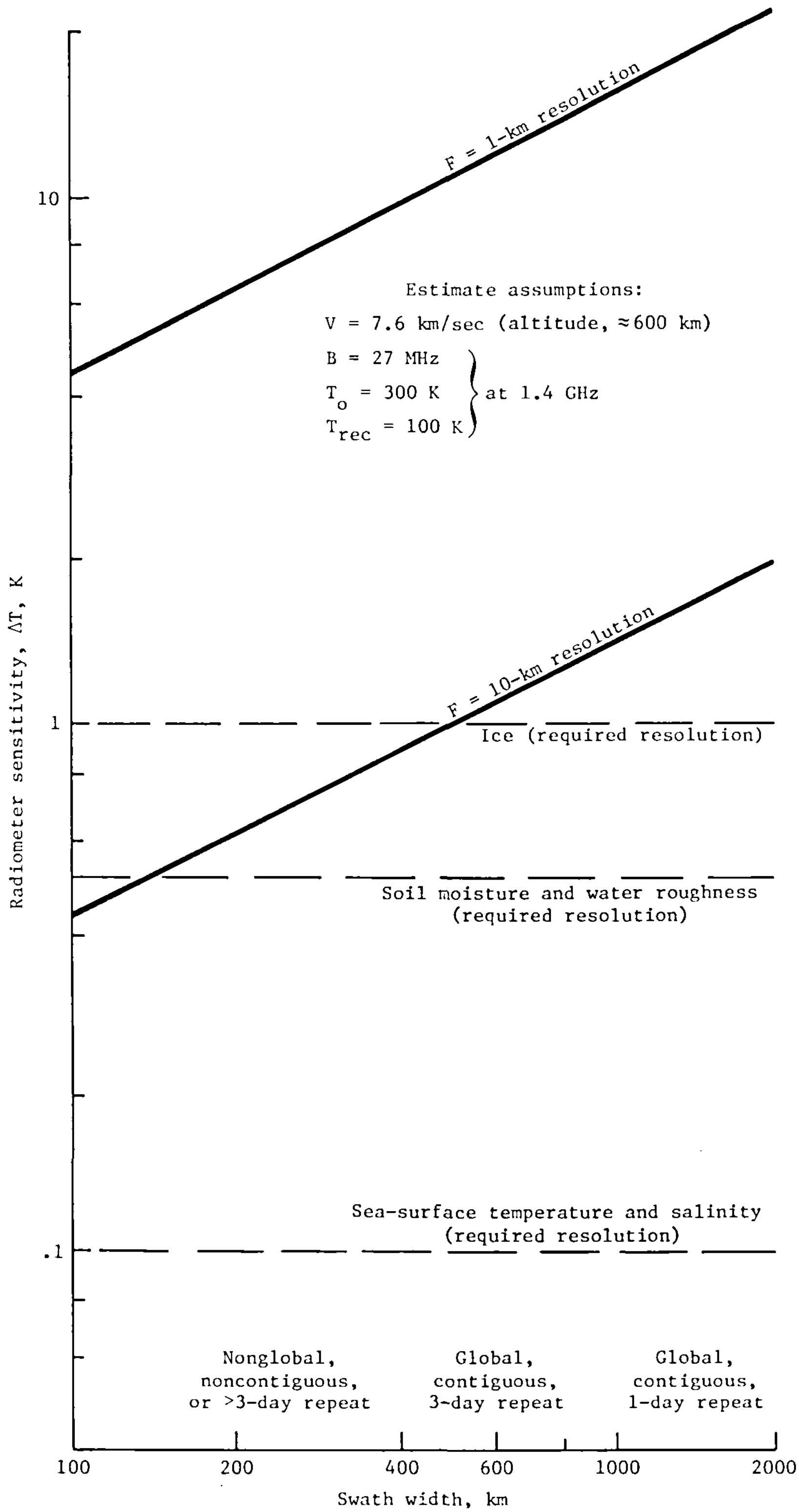


Figure 12.- Typical temperature sensitivity plotted against swath width for modeled single-beam radiometer.

Figure 12 shows that in order to meet the global, contiguous-coverage, high-resolution requirement for any of the measurands, except ice, steps must be taken to reduce values of ΔT dramatically (i.e., improve radiometer capability) below the values typical of real single-beam-scanned radiometers as represented by the one modeled. The minimum-allowable measurement integration time for a single-beam cross-track scan system with 10-km resolution and 600-km swath is approximately 0.025 sec. By taking into consideration real radiometer systems, this is generally an insufficient time for measurements with ΔT less than 0.5 K. It is obvious, therefore, that real LSA radiometer systems will likely have to utilize multiple-beam concepts in order to meet requirements for frequency range of operation, swath width, spatial resolution, and temperature sensitivity.

There are two basic systems for effecting multiple-beam operation: (1) Phased-array systems intercept the whole wave front impinging on the microwave antenna aperture and adjust signal phases electronically to form beams which may be fixed or scanned to obtain the swath widths required; and (2) reflector systems utilize multiple-feed arrays with a single large reflector. Multiple-beam reflector systems can be configured for "push-broom" operation (fixed beams with orbit-velocity scan only) or for "whisk-broom" operation (multiple beams with mechanical crosstrack and orbit-velocity scan).

For reflector systems, large angular fields of view necessary for wide swaths can best be obtained with multiple-beam configurations whose illumination areas on the reflector do not fully overlap, thus resulting in the requirement for a reflector whose size may be appreciably larger than the aperture size for a single beam.

Image Quality and Beam Efficiency

Image-quality requirements impose a severe beam-efficiency requirement on reflector systems which, in turn, impose reflector-surface irregularity and shape-distortion limits which are related to the wavelength of operation. The reflector-surface material or finish and the structural distortion under thermal cycling are the important considerations. Reflector-error tolerances fall somewhere within the range from $\lambda/30$ to $\lambda/100$ for random roughness ($\lambda/55$ is equivalent to a 5-percent loss in beam efficiency) and within the range from $\lambda/16$ to $\lambda/32$ for large-scale-shape (thermally or otherwise deterministic) distortion.

Other image-quality requirements (adapted from ref. 10) are as follows:

(1) The variations in resolution-element sizes F for a multiple-beam system shall not exceed ±10 percent of the average for all beams.

(2) Allowable deviations from perfect contiguity and cross-scan alignment of the resolution elements are as follows:

(a) Static cross-scan contiguity: Gaps between individual resolution elements and overlaps of resolution elements shall not exceed $1F$.

(b) Static along-scan displacement: Shall not exceed $2F$.

(c) Static-image distortion of a group of resolution elements: Although contiguity may be maintained with some types of image distortion, the cross-scan or along-scan displacement of any single resolution element from its ideal position shall not exceed $2F$.

(d) Dynamic deviations: Jitter or oscillatory deviations of any kind with equivalent spatial wavelengths of less than 500F shall not exceed a peak amplitude of 0.5F.

(3) Allowable deviations from perfect registration of resolution elements are defined as follows:

Deviation category	Global	Over control points
Temporal-registration offsets between two images over same area	<5F	<0.5F
Geodesic accuracy of an image	<5F	<0.5F
Uncertainty between two adjacent images from different passes ...	<5F	<0.5F
Rotation between adjacent images from different passes	<3°	<1.0°

Detailed system requirements for the number of beams, beam alignment, scanning technique, spacecraft-attitude accuracy, reflector tolerances, and other configuration or design-dependent parameters can be derived from the basic requirements by keeping in mind their interdependence as depicted in figure 11.

CONCLUSIONS

Conclusions regarding radiometer requirements for Earth-observation systems using large space antennas are presented in the following five groups:

Earth-Observation Requirements

1. Microwave sensing of a variety of geophysical phenomena on a global scale is required to support agricultural, hydrological, meteorological, atmospheric, and oceanographic applications.

2. Potential measurands for radiometers using large space antennas (LSA) include soil moisture, sea-surface temperature, salinity, water roughness (winds), and ice.

3. Measurements made with moderate-resolution passive microwave systems capable of contiguous mapping of large regions of the Earth with frequent revisits will complement high-resolution measurements made over limited areas with optical systems and active microwave systems.

Key-Measurement Requirements

4. Soil moisture and sea-surface temperature are key measurands because they require an LSA system and drive-technology developments.

5. Many application needs are met with approximately 10-km resolution. A number of applications, however, require resolutions as fine (small) as 1 km. Therefore, the spatial requirement ranges from 10 km (mandatory) to 1 km (desired).

6. Most application needs are met with temporal-repeat intervals of approximately once every 3 days. A few applications, however, require repeats as often as one per day. Therefore, 3 days is considered the primary requirement for temporal resolution; and 1 day, the secondary requirement.

7. Contiguous coverage of large geographic areas is vital to full utilization of the various measurements, for example, soil-moisture measurements over major farm belts.

8. Climate applications have the greatest need for measurements over long periods of time. A precise specification is not needed for technology-development purposes; thus, the requirement for experiment lifetime is stated simply as "several years."

Orbit Requirements

9. The radiometer must operate at an altitude in the range from 450 to 2200 km in order to obtain spatial resolution from 1 to 10 km with antenna apertures from 50 to 200 m and to satisfy lifetime, coverage, repeat, and incidence-angle requirements.

10. Orbit-inclination choices range from 60° to 98°. The important farm belts and ocean areas are covered with an inclination as low as 60°. Sun-synchronous sampling and possibly the avoidance of Sun glint will require a 98° inclination.

11. Swath widths of 300 km or more are required in order to obtain contiguous coverage with the required temporal resolution.

12. Active maintenance of the average orbit altitude may be required to maintain precise temporal-repeat intervals and geodetic precision of mapped-data products.

Radiometer Requirements

13. For the complete list of measurements and for the antenna-aperture range from 50 to 200 m, the frequency range to be considered is approximately from 1 to 37 GHz.

14. The key measurements (soil moisture and sea-surface temperature) require the lower frequencies (1 to 10 GHz) and the larger apertures (approaching 200 m for a 1-km spatial resolution).

15. Dual-polarization (or single linear, nonrotating polarization) measurements are required because of inversion errors caused by emissivity effects at large off-normal angles (>30°) of the emitted microwave radiation.

16. Main-beam efficiencies greater than 90 percent are required for Earth radiometry in order to obtain good image quality and to avoid smearing of heterogenous scenes.

17. An extremely large, angular-system field of view (60° or more) is required to meet the contiguous-mapping and wide-swath requirements.

18. The dynamic range in terms of brightness temperature is approximately 3 K to 340 K.

19. For the required spatial resolution, the systematic error in derived brightness temperature must be less than approximately 2°C to 3°C.

20. Brightness-temperature resolution requirements range from approximately 0.1 K to 0.5 K.

21. Radiometric-system noise temperature must be low over the frequency range to achieve sensitivities dictated by brightness-temperature precision and resolution requirements.

22. Within the range of system noise and bandwidth of typical radiometers, a brightness-temperature sensitivity of approximately 0.5 K is achievable and the mandatory spatial-resolution requirement of 10 km can be met for most measurands.

System-Design Requirements

23. For a typical radiometer, spatial resolution better (smaller) than 10 km requires longer dwell times than can be provided by a scanning single-beam system.

24. Real LSA radiometer systems will likely have to utilize multiple-beam concepts in order to meet the requirements for frequency range of operation, swath width, spatial resolution, and brightness-temperature sensitivity.

25. The requirement for a large angular-system field of view can best be met with multiple-beam concepts whose illumination areas on the reflector do not fully overlap, thus resulting in the requirement for a reflector whose size is appreciably larger than the aperture size for a single beam.

26. Beam-efficiency requirements impose reflector irregularity and structural-distortion limits which are related to the wavelength of operation and the size of the antenna aperture.

27. Reflector-error tolerances (which depend on aperture size, inherent beam efficiency of the feed and illumination designs, and side-lobe power-loss budget)

fall somewhere within the following ranges, expressed in terms of fractions of the operating wavelength λ.

Random roughness: $\lambda/30$ to $\lambda/100$

Large-scale-shape (deterministic) distortion: $\lambda/16$ to $\lambda/32$

28. Detailed system requirements for the number of beams, beam alignment, scanning technique, spacecraft-attitude accuracy, reflector tolerances, and related design-dependent parameters can be derived from the measurement, orbit, radiometer, and general system requirements delineated herein.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
April 14, 1983

REFERENCES

1. Keafer, Lloyd S., Jr.; Swanson, Paul; and Eckerman, Jerome: Radiometer Mission Requirements for Large Space Antenna Systems. NASA TM-84478, 1982.

2. NASA Space Systems Technology Model - Volume I, Part A: Mission Systems Descriptions and Technology Needs. NASA, 1981. (Available as NASA TM-80473.)

3. Staelin, David H.; and Rosenkranz, Philip, W., eds.: High Resolution Passive Microwave Satellites. Contract NAS5-23677, Massachusetts Inst. Technol., Apr. 14, 1978. (Available as NASA CR-160041.)

4. Bernstein, R. L.: Sea Surface Temperature Mapping With the SEASAT Microwave Radiometer. J. Geophys. Res., vol. 87, no. C10, Sept. 20, 1982, pp. 7865-7872.

5. Saunders, R. W.; Ward, N. R.; England, C. F.; and Hunt, G. E.: Satellite Observations of Sea Surface Temperature Around the British Isles. Bull. American Meteorol. Soc., vol. 63, no. 3, Mar. 1982, pp. 267-272.

6. Rangaswamy, S.; and Grover, James: Determination of Sea Surface Temperatures From Microwave and IR Data. NAS5-26179, Research and Data Systems, Inc., [1982]. (Available as NASA CR-166816.)

7. Soil Moisture Working Group: Plan of Research for Integrated Soil Moisture Studies. NASA, 1980. (Available as NASA TM-84731.)

8. Hardy, Kenneth R.; Cohen, Stephen H.; Rogers, Linda Koshio; Burke, Hsiao-Hua K.; Leupold, Robert C.; and Smallwood, Michael D.: An Evaluation of the Spatial Resolution of Soil Moisture Information. Document No. P-7505-F (Contract No. NAS5-25527), Environmental Research & Technology, Inc., Mar. 1981.

9. Brooks, D. R.; Bess, T. D.; and Gibson, G. G.: Predicting the Probability That Earth-Orbiting Spacecraft Will Collide With Man-Made Objects in Space. IAF Paper A74-34, Sept. 1974.

10. Keafer, Lloyd S., Jr.: Mission Definition for a Large-Aperture Microwave Radiometer Spacecraft. The Microwave Radiometer Spacecraft - A Design Study, Robert L. Wright, ed., NASA RP-1079, 1981, pp. 17-32.

11. Brooks, David R.: An Introduction to Orbit Dynamics and Its Application to Satellite-Based Earth Monitoring Missions. NASA RP-1009, 1977.

12. Litman, Viqui; and Nicholas, John: Guidelines for Spaceborne Microwave Remote Sensors, First ed. NASA RP-1086, 1982.

13. Webster, William J., Jr.; Wilheit, Thomas T.; Ross, Duncan B.; and Gloersen, Per: Spectral Characteristics of the Microwave Emission From a Wind-Driven Foam-Covered Sea. J. Geophys. Res., vol. 81, no. 18, June 20, 1976, pp. 3095-3099.

14. Hollinger, J. P.: Passive Microwave Measurements of Sea Surface Roughness. IEEE Trans. Geosci. Electron., vol. GE-9, no. 3, July 1971, pp. 165-169.

15. Lame, D. B.; and Born, G. H.: SEASAT Measurement System Evaluation: Achievements and Limitations. J. Geophys. Res., vol. 87, no. C5, Apr. 30, 1982, pp. 3175-3178.

16. Wang, J. R.; Schmugge, T. J.; Gould, W. I.; Glazar, W. S.; and Fuchs, J. E.: A Multi-Frequency Radiometric Measurement of Soil Moisture Content Over Bare and Vegetated Fields. Geophys. Res. Lett., vol. 9, no. 4, Apr. 1982, pp. 416-419.

17. Born, Max; and Wolf, Emil: Principles of Optics, Second rev. ed. Macmillan Co., c.1964.

18. Glodberg, I. L.; and McCullock, A. W.: Annular Aperture Diffracted Energy Distribution for an Extended Source. Appl. Opt., vol. 8, no. 7, July 1969, pp. 1451-1458.

19. Ruze, John: Antenna Tolerance Theory - A Review. Proc. IEEE, vol. 54, no. 4, Apr. 1966, pp. 633-640.

1. Report No. NASA RP-1101	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle RADIOMETER REQUIREMENTS FOR EARTH-OBSERVATION SYSTEMS USING LARGE SPACE ANTENNAS		5. Report Date June 1983
		6. Performing Organization Code 506-62-23-01
7. Author(s) Lloyd S. Keafer, Jr., and Richard F. Harrington		8. Performing Organization Report No. L-15429
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Reference Publication
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Requirements are defined for Earth-observation microwave radiometry for the decade of the 1990's by using large-space-antenna (LSA) systems with apertures in the range from 50 to 200 m. General Earth-observation needs, specific measurement requirements, orbit-mission guidelines and constraints, and general radiometer requirements are defined. This requirements definition has been assembled by the National Aeronautics and Space Administration (NASA) for the purpose of guiding the development of LSA spacecraft technology. General Earth-observation needs are derived from NASA's basic space-science program. Specific measurands include soil moisture, sea-surface temperature, salinity, water roughness, ice boundaries, and water pollutants. Measurements are required with spatial resolution from 10 to 1 km and with temporal resolution from 3 days to 1 day. The primary orbit altitude and inclination ranges are 450 to 2200 km and 60° to 98°, respectively. Contiguous large-scale coverage of several land and ocean areas over the globe dictates large (several hundred kilometers) swaths. Radiometer measurements are made in the bandwidth range from 1 to 37 GHz, preferably with dual-polarization radiometers with a minimum of 90-percent beam efficiency. Reflector-surface, root-mean-square deviation tolerances are in the wavelength range from 1/30 to 1/100. Accuracy and resolution requirements for brightness temperature are on the order of 2 K and 0.5 K, respectively, thus dictating a radiometer sensitivity of 0.5 K or lower. System implications point toward multiple-beam configurations used in either "whisk-broom" or "push-broom" modes.

17. Key Words (Suggested by Author(s)) Large-space-antenna systems Earth microwave radiometry Radiometer-mission requirements		18. Distribution Statement Unclassified - Unlimited Subject Categories 19, 43, 35	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 45	22. Price A03

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1983

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

THIRD-CLASS BULK RATE

Postage and Fees Paid
Nat
Spa
NA

NASA

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return